Computing Scour

by Craig Fischenich[1] and Mark Landers[2]

Complexity	Value as a Design Tool	Cost
Low Moderate High	Low Moderate	Low Moderate

OVERVIEW

Scour is the removal of soil particles by flowing water. While the entrainment of upland soils from overland runoff is included in this definition, scour on river systems generally refers to the removal of material from the bed and banks of the river from streamflow.

PLANNING

Total scour on a river is composed of three components 1) general scour, 2) contraction scour, and 3) local scour. In general, the components are additive when addressing scour on the streambed.

General Scour: Lowering of streambed elevation (also called bed degradation) over long reaches due to head cuts and changes in hydrology controls (such as dams, sediment discharge, or river geomorphology) is termed general scour. General scour often occurs during the passage of a flood, but is sometimes masked because sediments deposit to the original lines and grades on the falling stage of the hydrograph. General scour involves the removal of material from the bed and banks across all or most of the width of a channel. This type of scour may be natural or man-induced and requires geomorphic and sedimentation analyses to quantify. Analytical tools such as HEC-6 are helpful in evaluating long-term general scour.

Contraction Scour: The scour that results from the acceleration of the flow due to a contraction, such as a bridge, is called contraction scour. This type of scour also occurs in areas where revetments are placed such that they reduce the overall width of the stream segment. Contraction scour is generally limited to the length of the contraction, and perhaps a short distance up- and downstream, whereas general scour tends to occur over longer reaches.

Laursen's Equation (1960), given below, is often used to predict the depth of scour in the contracted section. For a long contraction, Laursen's Equation will overestimate the depth of scour at the upstream end of the contraction or if the contraction is the result of bridge abutments and piers. But at this time, it is the best equation available. Note that the Manning n ratio can be significant in cases where sand bed channels have variable bed forms (e.g. a dune bed in the uncontracted reach and a plain bed, washed out dunes or antidunes in the contracted reach).

$$\frac{y_c}{y_a} = \left(\frac{Q_c}{Q_a}\right)^{6/7}\left(\frac{W_a}{W_c}\right)^{A}\left(\frac{n_c}{n_a}\right)^{B} \qquad (1)$$

and

$$y_s = y_c - y_a \qquad (2)$$

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where

y_s = scour depth (ft)
y_a = average depth in the main reach (ft)
y_c = average depth in the contracted section (ft)
W_a = width of the main reach (ft)
W_c = width of the contracted section (ft)
Q_a = flow in the main reach (cfs)
Q_c = flow in the contracted section (cfs)
n_a = Manning n for main reach $(s/ft^{1/3})$
n_c = Manning n for contracted section $(s/ft^{1/3})$

A and B are dimensionless transport coefficients from the following:

V*/ω	A	B
<0.5	0.59	0.07
1.0	0.64	0.21
>2.0	0.69	0.37

where

V_* = shear velocity (ft/s), given by $(gyS_f)^{0.5}$
ω = fall velocity of the D_{50} of bed material (ft/s)

Local Scour: The scour that occurs at a pier, abutment, erosion control device, or other structure obstructing the flow is called local scour. These obstructions cause flow acceleration and create vortexes that remove the surrounding sediments. Generally, depths of local scour are much larger than general or contraction scour depths, often by a factor of ten. Local scour can affect the stability of structures such as riprap revetments and lead to failures if measures are not taken to address the scour.

Factors that affect local scour include:
1) Width of the obstruction.
2) Projection length of the obstruction into the flow.
3) Length of the obstruction.
4) Depth of flow.
5) Velocity of the approach flow.
6) Size of the bed material.
7) Angle of the approach flow (angle of attack).
8) Shape of the obstruction.
9) Bed configuration.
10) Ice formation or jams.
11) Debris.

Width of obstruction has a direct effect on the depth of scour. Thus, the wider the obstruction, the deeper the scour. Though not addressed by most empirical relations, the ratio of obstruction width to channel width is probably a better measure of scour potential than is the obstruction width alone.

Projected length of an obstruction into the stream affects the depth of scour. With an increase in the projected length of an abutment into the flow, there is an increase in scour. However, there is a limit on the increase in scour depth with an increase in length. This limit is reached when the ratio of projected length into the stream to the depth of the approaching flow is about 25 (U.S. Federal Highway Administration 1990).

The streamwise length of a structure has no appreciable effect on scour depth for straight sections; however, when the structure is at an angle to the flow, the length has a very large effect. At the same angle of attack, doubling the length of a structure increases scour depth by as much as 33 percent. Some equations take the length factor into account by using the ratio of structure length to depth of flow or structure width and the angle of attack of the flow to the structure. Others use the projected area of the structure to the flow in their equations.

An increase in flow depth can increase scour depth by a factor of 2 or larger. For bridge abutments, the increase is from 1.1 to 2.15, depending on the shape of the abutment. Scour depth also increases with the velocity of the approach flow.

Size of the bed material affects scour depth, though the effect is generally a function of the time exposed to erosive flows. In other words, sediment size may not affect the ultimate or maximum scour but only the time it takes to reach it. Large particles in the bed material such as cobbles or boulders may armor plate the scour hole.

The angle of attack of the flow to an obstruction has a large effect on local scour, as does the shape of the structure. Structures angled such that they cause flow convergence increase scour, whereas structures angled such that they cause divergence of flow lines generally decrease scour. Streamlining structures reduces the strength of the horseshoe and wake vortices, effectively reducing ultimate scour depths.

In streams with sand bed material, the shape of the bed (bed configuration) affects the turbulence and flow velocity, which in turn affect the depth of scour. Ice and debris can increase both the local and general (contraction) scour. The magnitude of the increase is still largely undetermined. Debris can be taken into account in the scour equations by estimating the amount of flow blockage (decrease in width) in the equations for contraction scour.

Two simple relations for estimating local scour depths along structures follow. Both have been modified by this author from research conducted by others. The first is based upon Laursen's (1980) approach for scour at a bridge abutment and the second upon Froehlich's (1987) equations for live-bed scour at bridge crossings. Guidance for computing local scour at the toe of a riprap revetment is also given in EM 1110-2-1601 (USACE 1991). These techniques are based on empirical approaches and have high standard errors of estimates. Relations presented in EM 1110-2-1601 are applicable to bendways where the ratio of the maximum to minimum flow depths is between 1.0 and 3.0, and where the radius

of curvature is from 2.0 to 10 times the top width of the channel. The Modified Laursen equation is applicable to cases where the scour depth is less than four times the flow depth and where the encroachment (length of the structure projected normal to the flow) is less than seven times the flow depth. Froehlich's equations were based upon 170 live-bed scour measurements primarily in sand-bed streams. The relations presented below are forms of the Laursen and Froehlich equations modified by the authors based upon observed scour depths in sand- and gravel-bed streams.

Modified Laursen:

$$\frac{y_s}{y_a} = 1.3 \left(\frac{W_o}{y_a} \right)^{0.48} \qquad (3)$$

Modified Froehlich:

$$\frac{y_s}{y_a} = 2 \left(\frac{\theta}{90} \right)^{0.13} \left(\frac{W_o}{y_a} \right)^{0.43} F_r^{0.61} + 1.0 \quad (4)$$

where
- y_s = scour depth (ft) below the water surface
- y_a = depth of flow at the structure (ft)
- W_o = length of structure projected normal to flow (ft)
- θ = angle of embankment to flow (deg.)
- F_r = Froude number of flow upstream of abutment

The modified Laursen equation is based on sediment transport relations. It gives maximum scour and implicitly includes contraction scour. FOR THIS EQUATION, DO NOT ADD CONTRACTION SCOUR TO OBTAIN TOTAL SCOUR AT THE STRUCTURE OR IN THE SECTION. The modified Froehlich equation does not include contraction scour, but does include a safety factor (+1.0) that effectively accounts for contraction scour in most cases. Values computed from either method should be increased by $y_a/6$ for

sand bed streams if dunes are the expected bed form.

DESIGN

When designing a riprap section to stabilize a streambank, scour can be determined in one of two ways: 1) excavating to the maximum scour depth and placing the stone section to this elevation, or 2) increasing the volume of material in the toe section to provide a launching apron that will fill and armor the scour hole. Preference is generally given to option 2 because of ease of construction, cost, and environmental impacts associated with excavation of the streambed.

The volume of material added to the toe section must be sufficient to armor to the ultimate depth of scour. The authors use a somewhat conservative approach that assumes that the side slope in the scour hole is 1:2 and that the requisite thickness of the launched armor layer should be twice the D_{100} of the riprap gradation. Thus, the volume of stone in the toe section per ft of bankline is given by:

$$Vol = \frac{D_{100}\sqrt{5(Y_s)^2}}{13.5} \tag{5}$$

where

Vol = The volume of riprap required (cy)

D_{100} = The largest size of stone in the riprap (ft)

Y_s = the estimated scour depth (ft) below the bed ($y_s - y_a$)

APPLICABILITY AND LIMITATIONS

Techniques described in this technical note are based in part on empirical measurement of scour in the laboratory and field. As such, they are limited in applicability to the range of conditions for which the data were collected. Computed values for scour depth should be field-verified through observation of scour hole depths in the project reach. Maximum scour depth is often difficult to determine due to subsequent deposition of sediments during the hydrograph recession. Therefore, the use of scour chains or other measures of maximum scour depth is advocated.

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